Ecohydraulic Modeling of Humpback Chub Habitat in the Grand Canyon

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Abstract

The construction of Hoover Dam in 1933 and Glen Canyon Dam in 1963 has been detrimental to the native fishes of Grand Canyon National Park. Currently, five of the eight native fish species are either extirpated or listed as federally endangered. This paper will provide an overview of the status of Grand Canyon fishes and look at how we can assess changes to dam operations through the use of hydraulic modeling of habitat variables. Ecohydraulic models clearly show the negative impacts from hydropower peaking on the persistence of physical habitat conditions (water depths and velocities). Fixing this alone, however, will not correct the altered temperature regime and sediment loads that native fishes evolved with in the Grand Canyon.

Objectives

The goal of this paper is to understand the state of the native fishes in Grand Canyon National Park (GCNP) and how ecohydraulic modeling has been used to understand the impact of dam operations on habitat availability of one of the most critically endangered fish, the humpback chub (*Gila cypha*).

Background on Grand Canyon Fishes and Glen Canyon Dam impacts

Fish native to the Grand Canyon (GC) include the humpback chub (HBC), razorback sucker, bluehead sucker, flannelmouth sucker, speckled dace, Colorado pikeminnow, roundtail chub, and bonytail. The last three, the Colorado pike minnow, roundtail chub, and bonytail, have been extirpated from the GC National Park since the construction of Hoover Dam in 1933 and Glen Canyon Dam in 1963. Of the five native fish that remain, the humpback chub and razorback sucker are on the endangered species list. In fact, the razorback sucker was previously thought to be extirpated but was recently discovered in the National Park in extremely low numbers near the entrance to Lake Mead in 2012. The native fish community for the Colorado River Basin is unique with low species diversity but a high proportion of endemism (the condition of a species existing only in a particular geographic location.) This is likely due to the Colorado River's age, geographic isolation, and unique environmental conditions as compared to other North American rivers.

The historic Colorado River carried a large sediment load. The spring snowmelt delivered flows that often would exceed 2831 m^3/s (100,000 cubic feet per second) and deposited new sediment along the canyon walls. Summer flows would diminish to several thousand cubic feet per second (cfs), allowing the turbid waters to warm and salinities to increase (Webb et. al., 1999). Infrequent but heavy summer monsoons create debris flows within the GC's tributary channels and are a major contributor to the GC's morphology (Webb et al, 1989). Backwater habitats provided by sandbars and debris fans provided habitat for the HBC to find velocity refuge and warmer water. Today, the Colorado River flows clear and cold below Glen Canyon

Dam (GCD) until the confluence of the Little Colorado, a tributary that contributes significant sediment loads after storm events. Summer water temperatures in the Colorado River now generally do not exceed 14 C° (57 F°), whereas the Little Colorado often reaches 24 C° (75 F°) in the summer months. The HBC need spawning temperatures of at least 16 C° for egg incubation (Gorman and Stone 1999). Lastly, hydropower generation from GCD peaks during the day when demand is highest (hydropower peaking) leading to daily fluctuations in discharge that have been as large as 864 m^3/s. These are the conditions that have fundamentally changed the aquatic habitat for native fishes in the GCNP and led to their decline.

Aside from changes to the physical environment, non-native species introductions also present complications for the future of native GCNP fishes. Channel catfish were introduced to the Colorado River in the 1890's. Following the completion of GCD, rainbow and brown trout were planted below the dam to provide an extremely popular cold-water trout fishery. In total, there have been at least 24 species of non-native fish documented in GCNP (Haden 1992) including rainbow and brown trout (both cold-water fishes), and fathead minnows, red shiners, plains killifish, green sunfish, common carb, channel catfish, yellow and black bullhead, largemouth bass, and striped bass (all of which are warm-water fish). Striped bass and plains killifish are also adapted to moderately saline environments. Together, this complex assemblage of non-native fish and the interest in maintaining the popular cold-water sport fishery for trout makes managing for the native species difficult.

A Biological Opinion (BO) issued by the United States Fish and Wildlife Service (USFWS) in 1994 found that "the proposed operation of Glen Canyon Dam… …is likely to jeopardize the continued existence of the humpback chub and razorback sucker and is likely to destroy or adversely modify designated critical habitat" (USFWS 1994). In the issuance of a BO that finds jeopardy, the USFWS delivers "Reasonable and Prudent Alternatives" as alternative actions to avoid the likelihood of jeopardizing the continued existence of a species. The USFWS 1994 BO opinion led to the development of the High Flow Experiments (HFE) and the Low Summer Steady Flow (LSSF) experiments, the latter of which I will talk about in this paper.

On December 9, 2013, the National Park Service adopted The Comprehensive Fisheries Management plan which includes several provisions to support the recovery of native fish including translocation of HBC to potential new spawning grounds (e.g. Shinumu and Havasu Creeks, which are tributaries) and the continued removal of non-native trout in the core area of the HBC population (NPS 2013). The discussion of a temperature control device on Glen Canyon Dam has been halted due to cost and fear of increasing competition from the previously mentioned non-native warm-water fishes.

Introduction to Ecohydraulic Modeling

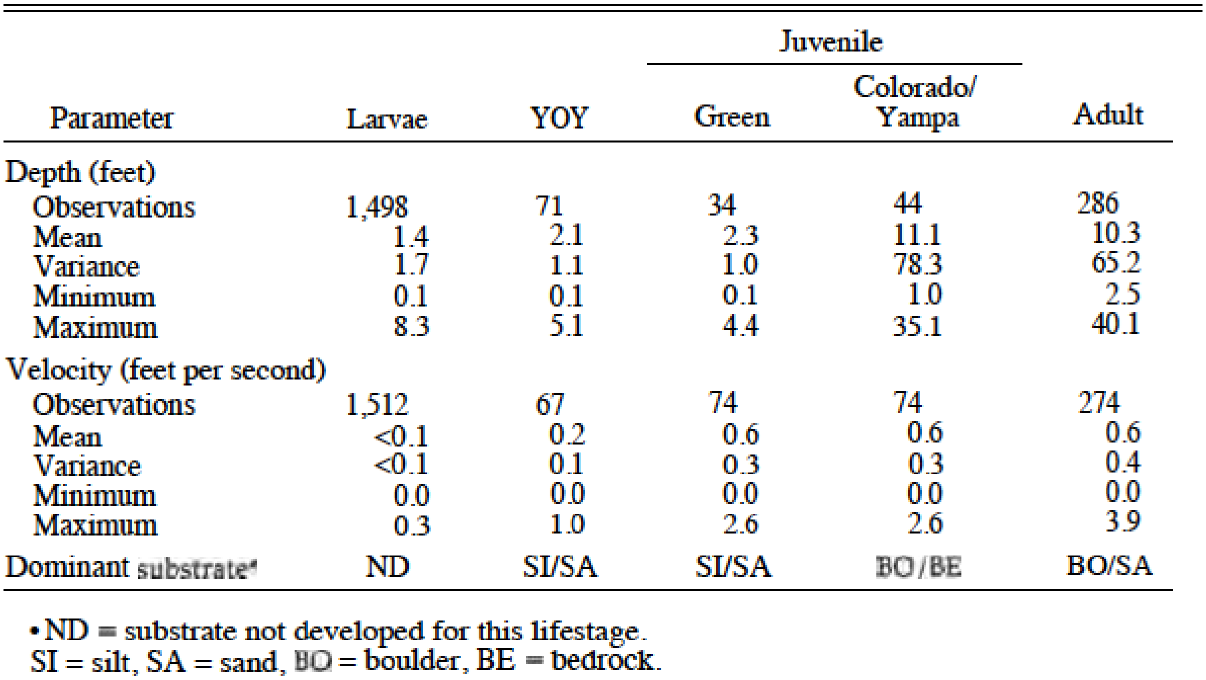
Ecohydraulic modeling is an emerging field of science that relates physical habitat variables such as water depth, velocity, turbulence, and substrate to characterize riverine ecosystem processes or functions. When used for fish habitat modeling, often what is done is to develop a Habitat Suitability Curve (HSC) for each of the inputs such as water depth, velocity, and substrate size or type. The HSC represents the species preferences for the range of hydraulic and physical habitat variables and is determined by extensive field data. After HSC's are developed, then hydrodynamic models, which are numerical models that solve for the physics of water movement, can be used to understand the hydraulic properties within the river (water depth, velocity magnitude and direction, bed shear stress,…etc.) at a range of discharges. Those model outputs can be translated into a habitat suitability index, and knowledge about different flow regimes' impacts to habitat available can be interpreted.

Applications of Ecohydraulic Modeling in the Grand Canyon

The focus on this section will be on the HBC due to its endangered status and the fact that the razorback chub was only recently discovered in GCNP. Thus, little information exists on the razorback chub's population status within the canyon and its habitat preferences.

The earliest attempt at identifying physical habitat characteristics for the HBC was by Valdez et al. (1990), who developed depth, velocity, and substrate statistics for four life stages of the HBC in the Upper Colorado River Basin (Green River and Colorado/Yampa River) (**Table 1**).

Table 1. Depth, velocity and substrate statistics associated with habitat suitability curves (HSC) for the four life stages of humpback chub in the Upper Colorado River Basin (Valdez et. al., 1990)



			Juvenile		
Parameter	Larvae	YOY	Green	Colorado/ Yampa	Adult
Depth (feet)					
Observations	1,498	71	34	44	286
Mean	1.4	2.1	2.3	11.1	10.3
Variance	1.7	1.1	1.0	78.3	65.2
Minimum	0.1	0.1	0.1	1.0	2.5
Maximum	8.3	5.1	4.4	35.1	40.1
Velocity (feet per second)					
Observations	1,512	67	74	74	274
Mean	<0.1	0.2	0.6	0.6	0.6
Variance	<0.1	0.1	0.3	0.3	0.4
Minimum	0.0	0.0	0.0	0.0	0.0
Maximum	0.3	1.0	2.6	2.6	3.9
Dominant substrate•	ND	SI/SA	SI/SA	BO/BE	BO/SA

• ND = substrate not developed for this lifestage.
SI = silt, SA = sand, BO = boulder, BE = bedrock.

Similar to many other riverine fishes, the larvae through juvenile stage of the HBC relies on shallow (< 3 ft) and slow-moving waters (< 1 ft/s) to develop because their swimming capabilities prevent them from occupying fast water and their vulnerability to predation makes deep water risky. The adult life stage of HBC is more variable in its depth habitat preferences, but was generally found in deeper waters than the young life stages with a mean depth of 10.3

feet. Velocity preferences for adult HBC were similar, with the majority of fish existing in waters below 1 ft/s, though a few fish were found in swift waters greater than 3 ft/s. The substrate statistics generally show that young-of-year (YOY) fish were found in areas with fine-grained sediments (slit and sand), whereas juvenile and adult life stages were found in a diversity of substrates including sand, boulder, and bedrock.

Converse et al. (1998) attempted to further define HBC habitat by relating subadult preferences to shoreline cover types along three different geomorphic reaches within the mainstem of the Colorado River below the Little Colorado (**Figure 1**).

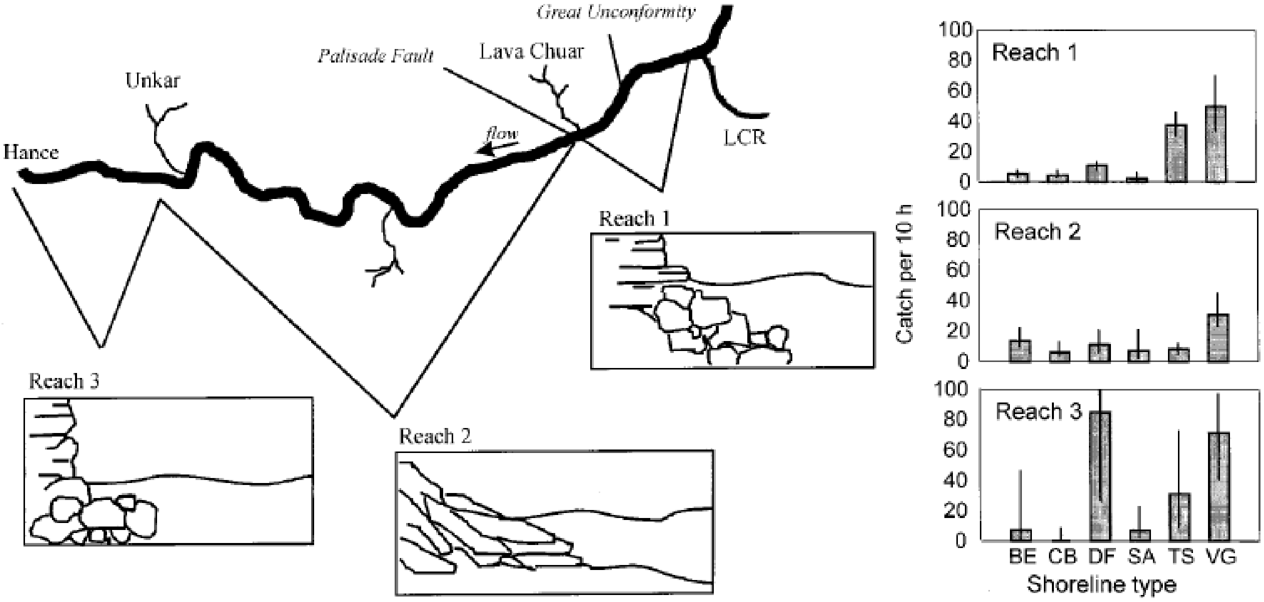
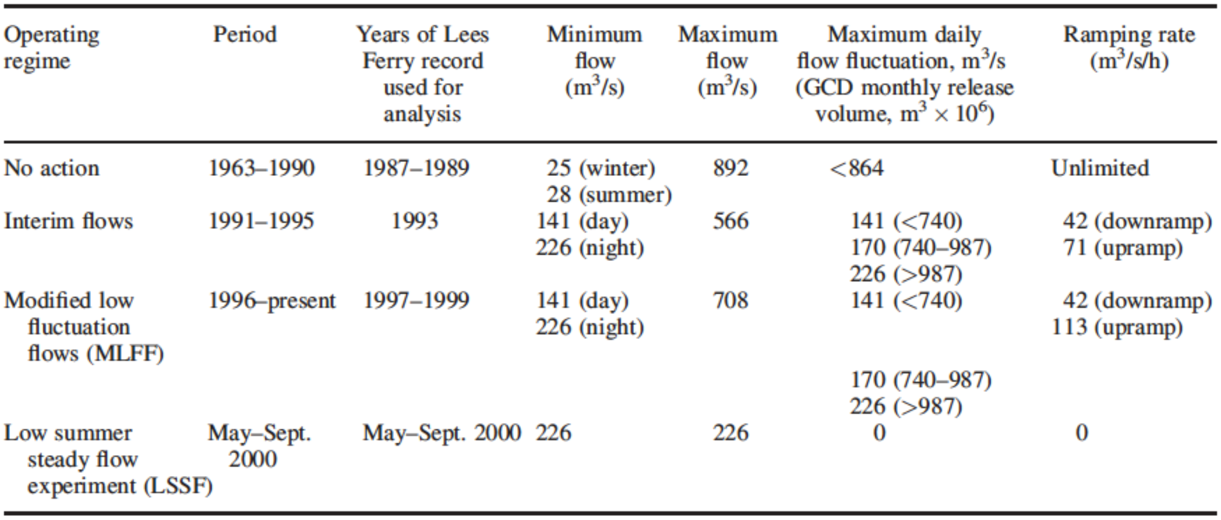


Figure 1. Map of geomorphic reaches and graph of shoreline habitat preferences of subadult humpback chub. BE = bedrock, CB = cobble, DF = debris fan, SA = sand, TS = talus, VG = vegetation.

Converse et al. (1998) found that vegetated shorelines, debris fans, and talus slopes were the preferred shoreline habitat (in that order). They also found that the density of cover was an important predictor regardless of shoreline type, and that the availability of cover decreased with increasing discharge.

Korman et al. (2004) used the knowledge developed by studies like Valdez et al. (1990) and Converse et al. (1998) to develop the first (to my knowledge) ecohydraulic model of HBC habitat. He applied a two-dimensional (2D) hydrodynamic model to explore seven reaches within the Grand Canyon to understand how the availability of suitable shoreline habitat and dispersal of humpback chub vary under different flow regimes (**Table 2)**. Analyzing these different flow regimes is important for understanding how past and current operations of GCD may be impacting river habitats. The period after GCD was constructed, 1963 – 1990, is called the “No action” operating regime where there were no restrictions on ramping rates for hydropower peaking and the maximum daily flow fluctuations were as high as 864 m^3/s (30,511 cfs). These daily hydropower peaking events are potentially detrimental to fish habitat availability and significantly increase the erosion of sandbar habitat. From 1991 – 1995, during the "Interim flows" operating regime, management of GCD changed while the United States Fish and Wildlife Service was working on a BO on the operations of GCD under the Endangered Species Act. Ramping rates were capped at 42 cubic meters per second per hour ($m^3/s/h$) for decreasing flows and 71 $m^3/s/h$ for increasing flows. The low summer steady flow (LSSF) operating regime comes from the 1994 BO by USFWS (USFWS 1994), where a steady low summer flow would be maintained to promote persistent habitat patches and allow velocity and thermal refuge for HBC to develop. The LSSF ran from May-September of 2000 and cost ~21 million dollars to purchase the lost power generation from GCD Korman et al. (2004).

Table 2. Summary of Glen Canyon Dam (GCD) operating regime characteristics (Korman et al., 2004).



Operating regime	Period	Years of Lees Ferry record used for analysis	Minimum flow (m^3/s)	Maximum flow (m^3/s)	Maximum daily flow fluctuation, m^3/s (GCD monthly release volume, $m^3 \times 10^6$)	Ramping rate ($m^3/s/h$)
No action	1963–1990	1987–1989	25 (winter) 28 (summer)	892	<864	Unlimited
Interim flows	1991–1995	1993	141 (day) 226 (night)	566	141 (<740) 170 (740–987) 226 (>987)	42 (downramp) 71 (upramp)
Modified low fluctuation flows (MLFF)	1996–present	1997–1999	141 (day) 226 (night)	708	141 (<740) 170 (740–987) 226 (>987)	42 (downramp) 113 (upramp)
Low summer steady flow experiment (LSSF)	May–Sept. 2000	May–Sept. 2000	226	226	0	0

Two significant findings from Korman et al. (2004) shed light on how operations of GCD have negatively impacted the HBC. First, the availability of suitable shoreline habitat for YOY and juvenile HBC, which require slow and shallow waters and close proximity to cover, greatly diminishes across most of the studied reaches as discharge increases (**Figure 2**). This means that the increased summer flows from GCD potentially provide less available habitat than the historic summer low flows, at least for the juvenile stages of the HCD. Second, when comparing the differences between pre-dam conditions (approximated by the LSSF case), the no-action, and the modified low fluctuation flows (MLFF) operating regimes, the hydropower peaking in each of the latter two cases significantly decrease the availability of persistent suitable habitat area (**Table 3**). This would be defined as habitat patches that stay within the preferred conditions of HBC over the course of a day when the flows are increased for peak power generation.

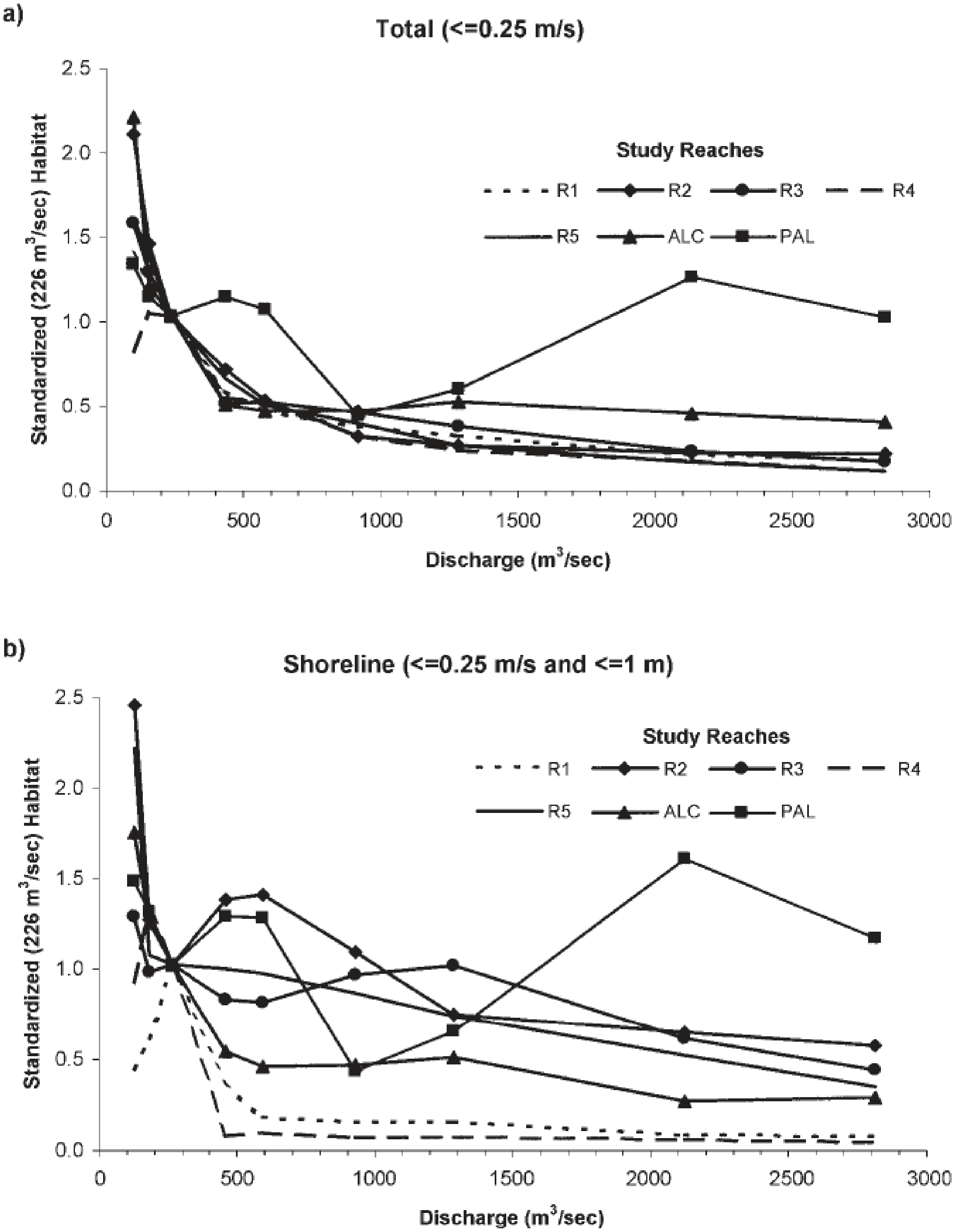
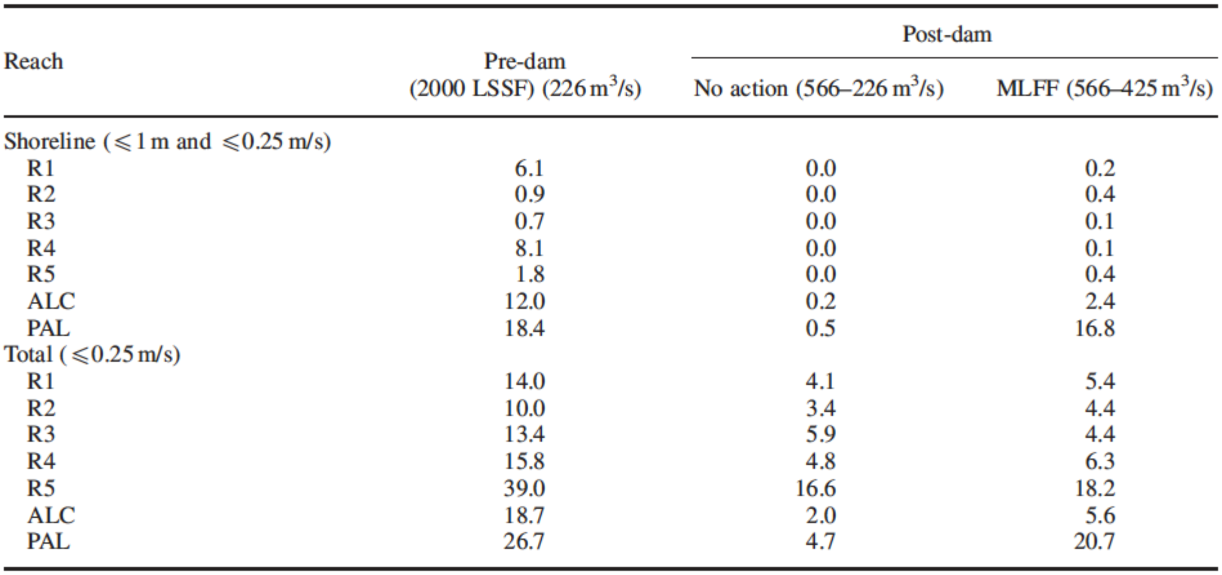


Figure 2. Habitat Suitability for HBC as a function of discharge as determined by the 2D hydrodynamic model. A) Shows total habitat below 0.25 m/s which would be suitable for adult HBC. B) Shows shoreline habitat which is below 0.25 m/s and < 1m in depth, which would be suitable for young of year and juvenile HBC (Korman et al., 2004).

Table 3. Persistent suitable habitat area (m^2 x 10^3) at daily discharge ranges typical of three historical GCD operating regimes (Korman et al., 2004).



Reach	Pre-dam	Post-dam	
	(2000 LSSF) (226 m^3/s)	No action (566–226 m^3/s)	MLFF (566–425 m^3/s)
Shoreline ($\leqslant$1 m and $\leqslant$0.25 m/s)			
R1	6.1	0.0	0.2
R2	0.9	0.0	0.4
R3	0.7	0.0	0.1
R4	8.1	0.0	0.1
R5	1.8	0.0	0.4
ALC	12.0	0.2	2.4
PAL	18.4	0.5	16.8
Total ($\leqslant$0.25 m/s)			
R1	14.0	4.1	5.4
R2	10.0	3.4	4.4
R3	13.4	5.9	4.4
R4	15.8	4.8	6.3
R5	39.0	16.6	18.2
ALC	18.7	2.0	5.6
PAL	26.7	4.7	20.7

Conclusion

Habitat modeling from Korman et al. (2004) clearly shows some of the negative consequences of flow regulation and hydropower peaking on the HBC in GCNP. Elevated summer flows diminish available shoreline habitat, which is critical for young HBCs. Hydropower peaking all but eliminates zones of persistent habitat across six of the seven study reaches. Whether habitat that is transient over the course of a day can even be considered suitable for the HBC remains unanswered. Finally, these ecohydraulic models only take into account hydraulic properties of habitat availability (depth and velocity), but HBC's evolved in water that was much warmer and more turbid. Without incorporating temperature into the habitat modeling, the conclusions are only part of the whole picture. Currently, no habitat that is available within the mainstem of the Colorado reliably reaches the temperature requirements necessary for spawning HBC. Thus, unless the management of GCD changes to increase summer temperatures, the survival of the HBC is dependent on the warm and turbid waters of the Little Colorado and the relocation programs to other tributaries of the Colorado River.

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